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DETERMINATION OF THE SIGN OF CARRIER TRANSPORTED ACROSS Si02 FILMS ON Si

Zeev A. Weinberg, et al

Princeton University

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Zeev A. Weinberg
Walter C. Johnson
Murray A. Lampert

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13. ABSTRACT

A technique has been developed for determination of the sign of charge carrier transported across an insulating film on a semiconductor substrate, utilizing the charge-carrier separation properties of a shallow p-n junction diffused into the semiconductor. For thermally grown SiO_2, unmetallized and contacted by a corona discharge in dry air, electrons are found to carry the current for both polarities of surface potential. Also demonstrated is electron-hole pair production in the Si by electrons entering from the oxide.

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Determination of the Sign of Carrier Transported Across SiO_2 Films on Si*

Z. Weinberg†, W. C. Johnson and M. A. Lampert

Department of Electrical Engineering, Princeton University,
Princeton, New Jersey 08540

In studying the charge transport properties of thin insulating films it is often difficult to determine whether the dominant carriers are electrons or holes. Yet, in the absence of this knowledge it is impossible to devise realistic models for the transport. In the course of study of breakdown in SiO_2 films on Si we have developed a p-n junction technique to solve this problem.

The basic idea is illustrated schematically in Fig. 1. Prior to formation of the insulating layer, the silicon substrate has had diffused into it a shallow p-n junction, using a p-type diffusion on n-substrate for negative surface potential of the insulating film (and the reverse of this for positive insulator surface potential) so as to avoid inversion of the thin layer at the silicon-insulator interface. The thickness of the diffused layer is made much smaller than the diffusion length of minority carriers so that this layer can act in a manner similar to the base region of a bipolar transistor. The shallow layer is connected externally to the substrate, and the built-in electric field of the p-n junction causes the junction to act as a sink for excess minority carriers in the thin region.

The operation of the structure is shown schematically in Fig. 1(a) for a negative insulator surface potential. The dominant charge carriers may be either electrons transported downward or holes transported upward. If the dominant carriers are electrons, they enter the shallow p-region of the Si as minority carriers and diffuse to the junction where they are swept into the n-substrate and give rise to the current I_n. To the extent that there is electron recombination in the p-region,

particularly at the oxide interface, there is also a small current in the p-circuit and a corresponding diminution in the n-circuit current. On the other hand, if the dominant carriers in the insulator are holes, these, being majority carriers in the p-region, will be ohmically relaxed and will give rise to a current I_p, with negligible current in the n-circuit. In such manner do the relative magnitudes of the two currents indicate the sign of the carrier. The configuration shown in Fig. 1(b), used for a positive insulator surface potential, operates in a manner analogous to that of Fig. 1(a). The effect of the large kinetic energy of carriers entering the narrow-bandgap semiconductor from the wide-bandgap insulator is discussed below.

We have applied the above-described technique to SiO_2 films thermally grown on Si to a thickness of approximately 1000 Å. The substrate was 5 ohm-cm Si, into which, prior to oxidation, had been diffused an 0.5 μm layer of opposite conductivity type having a surface impurity concentration of 10^{17} -10^{18} cm^{-3}. The surface of the oxide was unmetallized, contact to it being made by means of a corona discharge - either positive or negative - in dry air at atmospheric pressure. The experiment is illustrated in Fig. 2. The shield protects the top contact and the diode edges from the corona, and the shield voltage, V_s, is used to control the corona current, I_c, flowing into the diode. The active surface area of the sample was chosen to provide a suitable range of currents from the corona. The values of the current-sensing resistors, R_1 and R_2, must be much smaller than the diode internal resistance. In our experiment the voltage drops across R_1 and R_2 did not exceed 1 mV. The voltages across the resistors were measured with a Keithley Model 149 Nanovoltmeter.

The results of the experiment are as follows:

(i) Positive Charging [Fig. 1(b)]: $I_p = 0$, $I_n = I_c$, indicating electron transport through the oxide - a result consistent with other experimental evidence.[1]

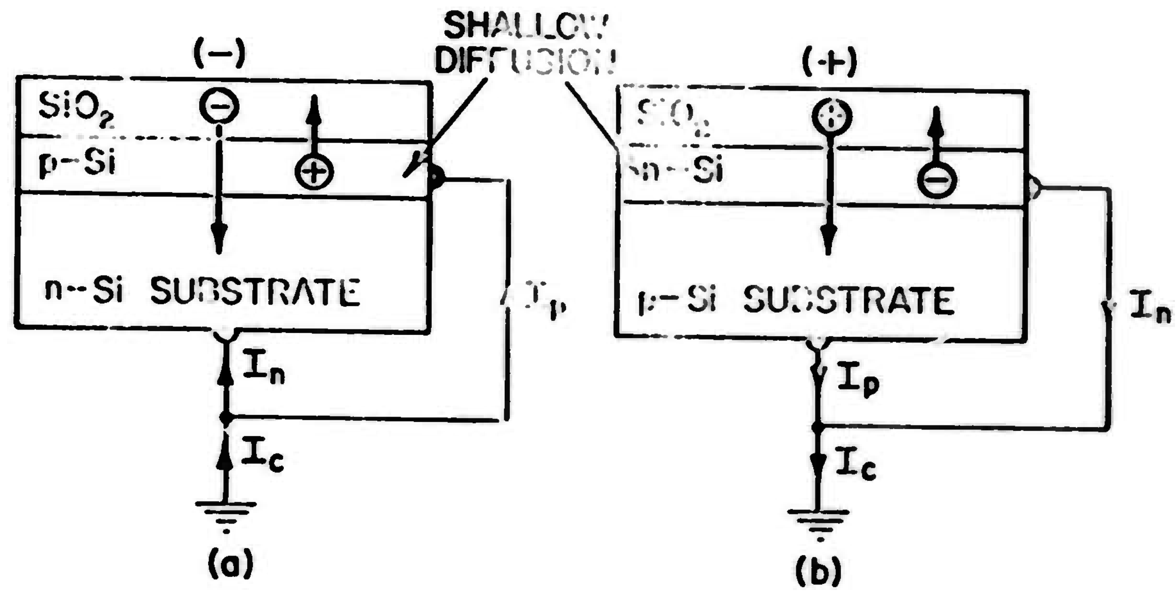

FIG. 1. Schematic illustration of the shallow p-n junction technique for charge-carrier discrimination: (a) for negative insulator surface potential, (b) for positive insulator surface potential. (Additional effects related to large kinetic energies are discussed in connection with Fig. 3.)

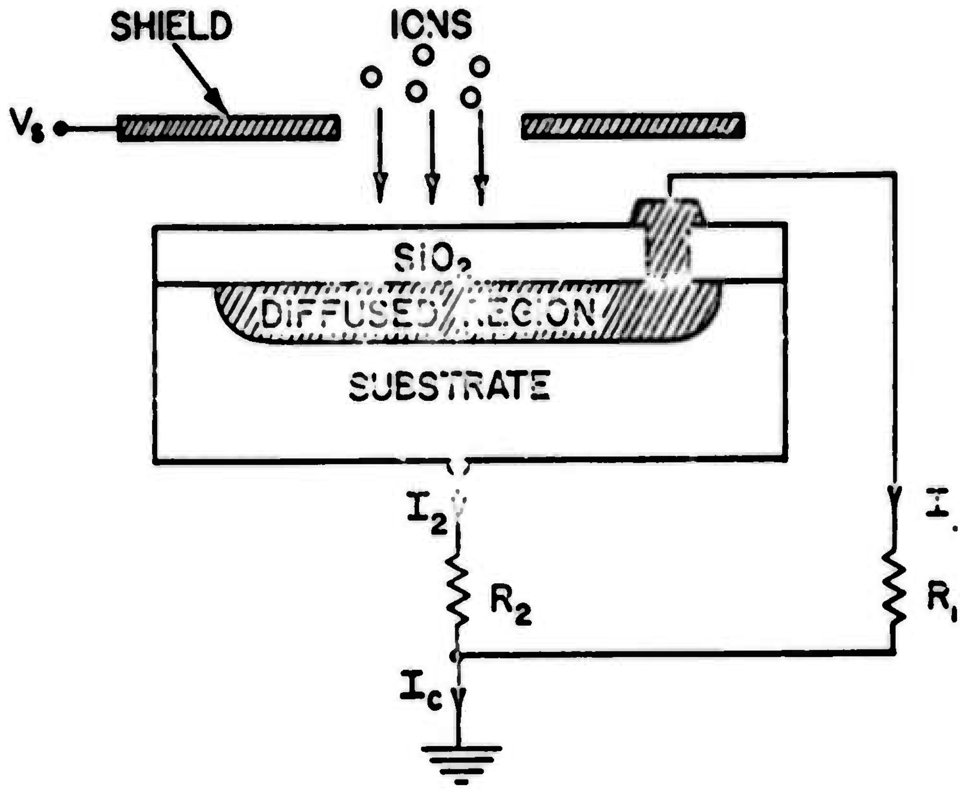

FIG. 2. Cross-sectional view of the diode experiment using corona charging. The shield opening was 1.5 mm x 3 mm. $R_1 = R_2 = 1\ k\Omega$.

(ii) <u>Negative Charging [Fig. 1(a)]</u>: The results are presented in Fig. 3. Currents are observed on both sides of the junction, with I_p <u>negative</u> (inconsistent with holes injected from the p-Si into the oxide) and I_n positive. The salient features of the data in Fig. 3 are: $I_p \approx -I_c$ and $I_n \approx 2I_c$. These results are readily explained by assuming that the dominant carriers in the oxide are electrons and that each electron, after entering the Si with at least 3.1 eV of excess kinetic energy,[2,3] generates, on the average, one electron-hole pair. Thus, for each electron entering the Si from the oxide, one hole, on the average, leaves the Si through the p-circuit and two electrons leave through the n-circuit.

We have demonstrated that photons arising in the corona discharge cannot be the source of the results shown in Fig. 3 by biasing the shield (Fig. 2) sufficiently positive to divert all negative ions from the sample, whereupon $I_p = 0$ and $I_n = 0$. There remains the formal possibility that photons generated by the ions settling on the surface may have played a key role. However, the result $I_p/I_n \approx -0.5$ would then require a coincidence beyond the reach of credulity.

In conclusion, we note that the diode experiments, in addition to identifying electrons as the dominant carriers in the SiO_2 for both polarities of corona discharge in dry air, also have demonstrated that the electrons in the conduction band of the oxide cannot, <u>on the average</u>, have been substantially heated-up at oxide fields up to 1×10^7 V/cm. The average electron in the oxide cannot have gained as much as 2 eV; otherwise at least two electron-hole pairs would have been generated per incoming electron, resulting in $|I_p/I_n| \geq 2/3$.

Our samples were fabricated at the RCA Laboratories in Princeton, N.J., and we express our gratitude to the many staff members at these Laboratories who furnished the necessary assistance.

References

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†Now at the IBM Laboratories, Yorktown Heights, N.Y.

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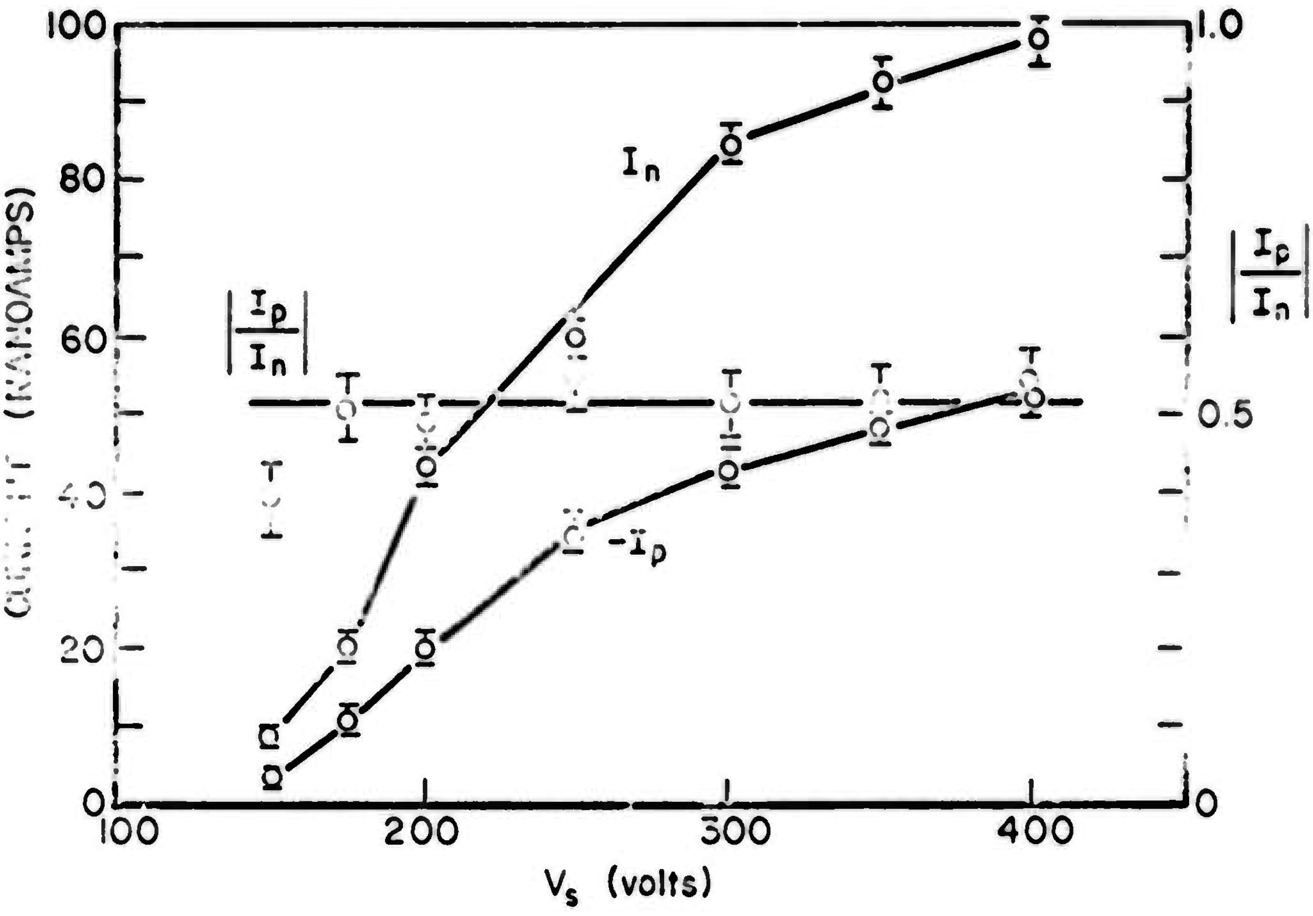

FIG. 3. Diode currents for negative corona charging. The average field in the oxide in these measurements was approximately 1.3×10^7 V/cm.